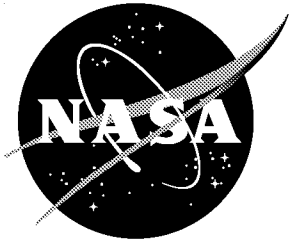


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Vibration Sensitivity of a Wide-Temperature Electronically Scanned Pressure Measurement (ESP) Module

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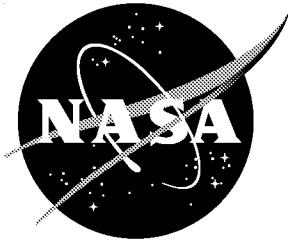
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VIBRATION SENSITIVITY OF A WIDE-TEMPERATURE ELECTRONICALLY SCANNED PRESSURE MEASUREMENT (ESP) MODULE

INTRODUCTION

The purpose of the measurements described in this memorandum is to determine the vibration sensitivity of a Wide-Temperature Electronically Scanned Pressure Measurement (ESP) Module. The test object is a 16-channel, 4-psid module designated as "M4" and designed to measure seal pressures in the Arc Sector of the National Transonic Facility. Since normal tunnel operations produce a significant vibrational environment, it is desirable to obtain test information on the effect of vibration on the response of the module.

An ESP module is a device containing silicon piezoresistive pressure wafers, with numbers varying from 16 to 64, to measure surface pressures on wind tunnel models or wall pressures in the tunnels themselves. The module is small enough to fit inside the model and is connected to surface pressure ports by means of nylon or other plastic tubing. A multiplexer internal to the module switches the sensors sequentially to a common output. In traditional cryogenic applications, as in the National Transonic Facility at Langley Research Center, the module is protected from the cryogenic temperatures by means of a heater box. The Wide-Temperature ESP module will operate directly in the cryogenic environment without the need of a heater box.

The experimental setup, test parameters, and test results will be described below.

NOMENCLATURE

D	Difference Between Hypothesized Means
f	Degrees of Freedom for t Critical Value
F, F^*	F Statistic
f_d	Degrees of Freedom for F Critical Value of Sample Denominator
f_n	Degrees of Freedom for F Critical Value of Sample Numerator
g	Induced Vibrational Acceleration
H_0	Null Hypothesis
H_a	Alternate Hypothesis
n	Sample Size
s	Sample Standard Deviation
s^2	Sample Variance
S^+	2.5 psid Slope for V_p Correction
S^-	-2.5 psid Slope for V_p Correction
s_p	Pooled Estimate of the Standard Deviation
t, t^*	Student's t Statistic
V	Volts
V_p	Pressure Voltage
$V_{p\text{ cor}}$	Corrected V_p

V_{t0}	Reference Temperature Voltage
V_t	Temperature Voltage
\bar{x}	Sample Mean
α	Significance Level
μ	Hypothesized Population Mean
σ^2	Population Variance

EXPERIMENTAL SETUP

A block diagram of the test instrumentation appears in Figure 1. Details of the test assembly are shown in Figure 2. Test module M4 is strapped to a mounting bar by means of tie wraps and the assembly screwed tightly onto the vibration table. An accelerometer is bonded to the top face of the test module. In the position shown, the acceleration is normal to the plane of the diaphragm in each silicon pressure sensor – a direction designated as parallel to the Z-axis. The pressure ports of the module are connected to a manifold, insuring that each port is subjected to the same differential pressure. The reference pressure port is exposed to the ambient atmosphere. A nylon tube connects the manifold to a System 8400, manufactured by Pressure Systems, Inc., which controls the differential step pressure and transmits the resulting voltage data to a host computer for storage. A cable assembly on the front face of the module connects the electrical output of each sensor to the System 8400. The module can be strapped similarly to the mounting bar to enable accelerations in the other two directions parallel to the sensor diaphragms.

A function generator applies a signal to a power amplifier to drive the vibration exciter at fixed frequencies. The signal from the accelerometer is received by an accelerometer power supply, measured on a voltmeter, and monitored on an oscilloscope. Since the sensitivity of the accelerometer is known (9.8 mV/g), the acceleration can be determined from the voltmeter reading. The purpose of the oscilloscope is to detect clipping or other sources of harmonic distortion in the accelerometer signal.

The vibration sensitivity is determined by measuring the response of the pressure sensors to a fixed step differential pressure with and without the vibration applied. A measurable difference would constitute the “vibration sensitivity,” specified as percent of full-scale output per g. All measurements were performed at room temperature.

DATA COLLECTION PROCEDURE

Data of interest is measured pressure voltage V_p and temperature voltage V_t for a given sensor. Module M4 is designed to house a total of 16 sensors that measure both pressure and temperature. V_p is a function of temperature, pressure, and vibration. V_t is assumed to vary in temperature only and is not vibration sensitive. Measurements of V_p and V_t are taken during conditions of vibration and no vibration at identical differential pressures and temperatures. This is done to gather data that is a function of vibration only. However, some temperature drift during the test must be accounted for since the module is open to an uncontrolled room-temperature environment.

The data gathering procedure begins with ten samples of V_p and V_t taken in rapid succession at the given test condition. Variables include module vibration acceleration level, vibration frequency (20, 55, and 75 Hz), differential pressure (2.5 and -2.5 psid), and module axis orientation (X, Y, and Z-axes). The positive step differential pressure is applied while the module is in the vibrationally unexcited state and ten samples of V_p and V_t are taken. The module is then excited into vibration with the desired vibration frequency and another ten voltage samples are taken in quick succession. This process is repeated during application of the negative differential step pressure. All data is taken at the same reference pressure, which is approximately 1 atm. An acceleration of 1 g is induced during application of all vibration frequencies in the test, except at 20 Hz induced vibration. Acceleration of 0.7g is induced at this frequency so that a good signal waveform is produced. Test data are gathered in groupings corresponding to vibration frequency and module axis orientation.

DATA EVALUATION

The vibration sensitivity of each module sensor is to be determined. Inferential statistics will be used to establish this sensitivity using sampled data. The two populations of interest for evaluation are V_p with and without vibration at the specified test condition, e.g. vibration frequency, differential step pressure, and axis orientation. Temperature drift is corrected for to eliminate any V_p change due to temperature fluctuation. Once temperature drift is corrected for, the difference in V_p between the two populations can be attributed solely to vibration effects.

Assumptions

It is assumed that the V_p populations are normally distributed and the randomly taken sample data are representative of the parent populations. The sample mean is used as a basis for inference of the population mean, which is the parameter used to characterize V_p . V_t is assumed to vary only in temperature, not vibration.

Temperature Correction

V_p is a function of differential pressure, temperature, and vibration. In order to compare V_p with and without module vibration, pressure and temperature dependency must be removed. This is accomplished by taking measurements at constant differential pressure and temperature. Differential pressure is made constant since it is accurately controlled by the PSI System 8400. Measurements are taken at either 2.5 or -2.5 psid. The module is left open to room temperature during data collection. Although this temperature is kept relatively constant, there is still some temperature drift. This must be compensated for to allow an accurate comparison between vibration and no-vibration V_p data. After correction, V_p becomes a function of vibration only.

For a given test condition, as defined above, measurements are acquired with and without vibration. All measured V_p in both sets, with and without vibration, are corrected to the temperature of the first measured V_p of the first set. The first set of ten data points is taken without the application of vibration. This temperature voltage at the first data

point is the reference temperature and will be referred to as V_{t0} . All other points in the two data sets deviate from this reference temperature condition due to temperature drift.

Using previous calibration data, the change in V_p due to V_t is found at the given test condition for the particular sensor. Using V_t associated with the V_p data point to be corrected, the change between V_t and V_{t0} is determined. This change is used to establish the correction factor to apply to V_p using the predetermined relationship between V_p and V_t found from calibration data. The resulting corrected values of V_p are a function of vibration only.

1. Procedural Example

For a given sensor, V_p and V_t are measured before and during the application of vibration at the given differential pressure. Before vibration is applied to the module, V_p data is a function of temperature. During vibration, V_p is a function of both temperature and vibration. The relationship between V_p and V_t for a sensor at a particular test pressure over the full temperature range, 50 to -175° Celsius, is found from previous calibration data. An example showing the correlation between V_p and V_t using calibration data for sensor 1 at 1 atm and 2.5 psid is shown in Figure 3. A tangent with slope

$S = \frac{\Delta V_p}{\Delta V_t}$ gives the change in V_p due to V_t at the test condition. A different slope is found

for each sensor at a given differential pressure of 2.5 and -2.5 psid. These will be referred to as S^+ and S^- , corresponding to the slope for 2.5 and -2.5 psid data. Using the method of least squares, two quadratic polynomials:

$$\begin{aligned} V_{p1} &= m_{21}V_t^2 + m_{11}V_t + b_1 \\ V_{p2} &= m_{22}V_t^2 + m_{12}V_t + b_2 \end{aligned}$$

are fit to the calibration data of V_p versus V_t for both 2.5 and -2.5 psid data. The fit given by V_{p1} corresponds to 2.5 psid data, while V_{p2} corresponds to the fit of -2.5 psid data. A sample fit is shown for sensor 1 at 1 atm and 2.5 psid in Figure 3. The quadratic equation for this fit is given by $V_{p1} = 0.1506V_t^2 - 0.0846V_t + 0.6679$. The derivatives of these quadratic equations with respect to V_t at the particular data point are S^+ and S^- . The expressions for the slopes of S^+ and S^- are given by:

$$\begin{aligned} S^+ &= \frac{dV_{p1}}{dV_t} = 2m_{21}V_t + m_{11} \\ S^- &= \frac{dV_{p2}}{dV_t} = 2m_{22}V_t + m_{12} \end{aligned}$$

For instance, the slope of sensor 1 at 1 atm, 2.5 psid, $V_p = 0.6949$ V, $V_t = -0.0482$ V, and $V_{t0} = -0.0401$ V is given by:

$$S^+ = \frac{dV_{p1}}{dV_t} = 2m_{21}V_t + m_{11} = 2(0.1506)(-0.0482) - 0.0846 = -0.0991$$

A different slope is calculated for each measured point to be corrected in the data set at both 2.5 and -2.5 psid for a given sensor.

At a vibration frequency of 20 Hz along the module's Z-axis, data was acquired with an application of 2.5 and -2.5 psid. Test data and the resulting slopes for sensor 1 of the module are shown in Table 1. V_p at the test frequency is corrected for by subtracting the calculated V_p change due to temperature fluctuation from the measured data point. V_p is corrected using the equation:

$$V_{p\text{cor}} = V_p - (S^\pm)[V_t - V_{t0}] \quad (1)$$

where S^\pm is the slope corresponding to either the 2.5 or -2.5 psid condition, V_{t0} is the reference temperature voltage of the data set, and V_p and V_t are the measured data points. For the example condition, $V_{p\text{cor}}$ is given by:

$$\begin{aligned} V_{p\text{cor}} &= V_p - (S^+)[V_t - V_{t0}] \\ &= 0.6949 - (-0.0991)[-0.0482 - (-0.0401)] \\ &= 0.6941 \end{aligned}$$

Corrected values of V_p for sensor 1 at a vibration frequency of 20 Hz along the module's Z-axis are shown in Table 1.

Small Sample Statistical Inference

Data measured with and without vibration can now be compared using corrected values of V_p . The twenty sample voltages measured during the experiment at various conditions are used to determine the effect of vibration on measured V_p . The Student's t test is employed to determine this effect [1,2]. This technique provides good statistical inference about a population using small samples, which have sizes less than or equal to thirty. The random samples taken under no vibration and vibration conditions are independent and unpaired and assumed to be taken from an approximately normally distributed voltage population. The population variable of interest is the mean of the pressure voltage V_p . This is used to quantify the effect of vibration on module output and is determined through the evaluation of sample means via small sample statistical inference. Specifically for this study, the t test will be used to infer the difference between two independent V_p population means.

Statistical inference concerning the value of a population parameter can take two forms. One involves making a decision about the hypothesized value of the parameter, while the other involves an estimate of the actual value. The first technique allows the hypothesis to be tested based on a pass or no-pass judging criterion. The second technique of estimation provides a point estimate of the population parameter with a probable range of values. The hypothesis testing procedure is used in this study to infer values of the population parameter.

1. Student's t Test Methodology

The distribution of the t statistic provides a measure of the probability that the measured variable lies near the mean within a given standard deviation of the population distribution using small sample data. This method is based primarily on the central limit theorem, which provides information on the distribution of the means of random samples with a given sample size. It also gives the relationship between population and sample parameters.

Testing the validity of a formulated hypothesis concerning the population allows inferences about the population parameter to be made. Testing begins with the formulation of the null hypothesis H_0 . This is the statement that the population parameter of interest has a particular value. An alternate hypothesis about the same population being different in value than the null hypothesis is also prepared. This is denoted by the variable H_a . Next, the test criterion is determined, which will allow a decision to be made on the validity of the hypothesis. This criterion provides critical regions of the t distribution on which to base hypothesis validity and is based on the assigned probability of rejecting a true null hypothesis, called a Type I error. This is represented by the significance level α . A value of 0.01 to 0.05 is usually assigned to α and indicates a 1 to 5% chance of making a Type I error during hypothesis testing. Finally, a decision is made on whether to reject the null hypothesis based on the calculated t statistic. Should this statistic fall in the critical region, the null hypothesis is rejected in favor of the alternate hypothesis. However, if the statistic falls within acceptable critical bounds, the null hypothesis cannot be rejected and is considered valid based on the sample data.

The Student's t statistic used to infer the population mean is given by the equation:

$$t = \frac{\bar{x} - \mu}{s/\sqrt{n}}$$

where \bar{x} is the mean of the sample data, μ is hypothesized population mean, s is the sample standard deviation, and n is the sample size. The t statistic is symmetrically distributed about a mean of 0 with a variance that approaches 1 as sample size increases. The t statistic is used when sample data size is less than or equal to thirty.

The form of the t statistic is modified slightly in order to make inferences concerning the difference between two independent population means. Two cases arise

with this form. The first involves the situation where the variances of the two populations are equal, $\sigma_1^2 = \sigma_2^2$, while the second involves unequal variances, $\sigma_1^2 \neq \sigma_2^2$. With equal population variances, the t statistic is found by the equation:

$$t = \frac{(\bar{x}_1 - \bar{x}_2) - (\mu_1 - \mu_2)}{s_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

where \bar{x}_1 and \bar{x}_2 are the sample means from the first and second populations, $(\mu_1 - \mu_2)$ is the hypothesized difference between the two population means, n_1 and n_2 are the sample sizes from the first and second populations, and s_p is the pooled estimate of the standard deviation given by the equation:

$$s_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}}$$

where n_1 and n_2 are the sample sizes from the first and second populations, and s_1^2 and s_2^2 are the variances from the first and second population samples. Here, $n_1 + n_2 - 2$ degrees of freedom are used to find the critical values at the user specified significance level α .

For unequal population variances, the t statistic is found by the equation:

$$t = \frac{(\bar{x}_1 - \bar{x}_2) - (\mu_1 - \mu_2)}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

where \bar{x}_1 and \bar{x}_2 are the sample means from the first and second populations, $(\mu_1 - \mu_2)$ is the hypothesized difference between the two population means, n_1 and n_2 are the sample sizes from the first and second populations, and s_1^2 and s_2^2 are the variances from the first and second population samples. The smaller of $n_1 - 1$ or $n_2 - 1$ degrees of freedom are used to determine the critical values at the specified significance level.

Values of population variances are usually unknown. Variance equality between two populations must be inferred using sample data by means of the F test. A hypothesis testing procedure, similar to the Student's t test, is followed for this type of test. The F statistic is given by the equation:

$$F = \frac{s_1^2}{s_2^2}$$

where s_1^2 and s_2^2 are the variances from the first and second population samples. Therewith, $n_1 - 1$ and $n_2 - 1$ degrees of freedom are used to determine the critical values at the specified significance level. The F distribution is nonsymmetrical with a mean of one and skewed to the right of zero. Values of the F statistic are positive and greater than or equal to zero. The null hypothesis, $H_0 : \sigma_1^2 = \sigma_2^2$, is tested against the alternate hypothesis, $H_a : \sigma_1^2 \neq \sigma_2^2$. Should the calculated F statistic fall within the critical region bounded by the critical values, there is enough evidence to conclude the null hypothesis is false. However, if the statistic does not fall in this region, there is insufficient evidence to reject the null hypothesis.

2. Procedural Example

An inference concerning two independent population means is to be made. The parameters of interest from these two populations are the pressure voltages V_p measured with and without induced vibration. It is unknown whether V_p measured during vibration will be greater or less than V_p measured without vibration at the test condition for a particular sensor. Therefore, two one-tailed t tests will be utilized to test both instances. The first will test for a difference of 0.0001 V between the two population means, whereas the second will test for a difference of -0.0001 V; 0.0001 V is initially chosen as the hypothesized difference since it is the measurement precision limit of the PSI 8400. The alternate hypotheses formulated are statements that the differences between the two population means are greater than 0.0001 V and less than -0.0001 V, respectively. This difference is given by the variable D . These two one-tailed t tests are expressed formally, with $\alpha = 0.05$, as:

- Test one
 - $H_0 : (\mu_1 - \mu_2) = 0.0001 \text{ V}$
 - $H_a : (\mu_1 - \mu_2) > 0.0001 \text{ V}$
- Test two
 - $H_0 : (\mu_1 - \mu_2) = -0.0001 \text{ V}$
 - $H_a : (\mu_1 - \mu_2) < -0.0001 \text{ V}$

where μ_1 is the hypothesized population average of V_p with no vibration and μ_2 is the hypothesized population average of V_p with vibration. A calculation example is shown below for sensor 1 data at 55 Hz vibration along the module's Z-axis with an application of 2.5 psid differential pressure.

The first step involves performing the F test to determine the equality of the population variances of V_p data with and without vibration. V_p data for sensor 1 at this

condition is shown in Table 2. A two-tailed F test is performed with $\alpha = 0.05$. The hypotheses are expressed as:

$$\begin{aligned} \circ \quad H_0 : (\sigma_1^2 - \sigma_2^2) &= 0 \\ \circ \quad H_a : (\sigma_1^2 - \sigma_2^2) &\neq 0 \end{aligned}$$

where σ_1^2 is the hypothesized population variance of V_p with no vibration and σ_2^2 is the hypothesized population variance of V_p with vibration. The F statistic for this example is given by:

$$F^* = \frac{s_1^2}{s_2^2} = \frac{(0.000113)^2}{(0.00024)^2} = 0.220974$$

In this example, s_1 is the standard deviation of $V_{p \text{ cor}}$ without vibration and s_2 is the standard deviation of $V_{p \text{ cor}}$ with vibration. Critical values of the F statistic are found from F distribution tables found in most statistical books [1,2]. These values are given by $F(f_n, f_d, \alpha)$, where f_n is the degrees of freedom of the sample of the numerator, f_d is the degrees of freedom of the sample of the denominator, and α is the significance level. The left and right critical values of F , $F(9, 9, 0.975)$ and $F(9, 9, 0.025)$, are 0.248 and 4.03, respectively. The F statistic found using the sample variances lies within the rejection region of the F distribution ($F \leq 0.248139$ or $F \geq 4.03$). The null hypothesis is rejected in favor of the alternate. There is sufficient evidence from sample data to conclude the variances of the population of V_p with and without vibration are unequal. The t test involving unequal population variances will be used for this particular sensor at this test condition.

The t statistic for the hypothesis that $(\mu_1 - \mu_2) = 0.0001 \text{ V}$ is given by:

$$t^* = \frac{(\bar{x}_1 - \bar{x}_2) - (\mu_1 - \mu_2)}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} = \frac{(0.694729 - 0.694612) - (0.0001)}{\sqrt{\frac{0.000113^2}{10} + \frac{0.00024^2}{10}}} = 0.201616$$

Here, \bar{x}_1 is the average of $V_{p \text{ cor}}$ without vibration and \bar{x}_2 is the average of $V_{p \text{ cor}}$ with vibration. Sample sizes of $V_{p \text{ cor}}$ with and without vibration are n_1 and n_2 , respectively. Standard deviations of $V_{p \text{ cor}}$ with and without vibration are s_1 and s_2 , respectively. Critical values of the t statistic are found from Student's t distribution tables found in most statistical books [1,2]. These values are given by $t(f, \alpha)$, where f is the degrees of freedom of the sample data and α is the significance level. The right t critical value, $t(9, 0.05)$, is 1.83. The t statistic does not lie within the critical region ($t \geq 1.83$), therefore there is insufficient evidence to reject the null hypothesis.

The t statistic for the second hypothesis, $(\mu_1 - \mu_2) = -0.0001$, is given by:

$$t^* = \frac{(\bar{x}_1 - \bar{x}_2) - (\mu_1 - \mu_2)}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} = \frac{(0.694729 - 0.694612) - (-0.0001)}{\sqrt{\frac{0.000113^2}{10} + \frac{0.00024^2}{10}}} = 2.588288$$

The left critical value of t , $t(9, 0.95)$, is -1.83 . The t statistic does not lie in the critical region for this particular test ($t \leq -1.83$). There is insufficient evidence to conclude that the null hypothesis should be rejected. Therefore, it is concluded that the difference between the population means of V_p with and without vibration for sensor 1 at 55 Hz vibration along the module's Z-axis with an application of 2.5 psid differential pressure is no greater than 0.0001 V. Similar methodology is repeated for each sensor at a given differential pressure, vibration frequency, and axis orientation.

RESULTS

Results of the F and t tests for all working sensors and conditions for module M4 are given in Tables 3 through 20. Sensors 6, 11, and 14 for this particular module are not working and have not been evaluated. Sensor 8 of the module at 55 Hz vibration along the Y-axis with an application of 2.5 psid, sensors 1, 3, 12, and 16 at 20 Hz vibration along the X-axis with an application of -2.5 psid, and sensors 7 and 9 at 55 Hz vibration along the Z-axis with an application of 2.5 psid show increased vibration sensitivity. Sample evidence indicates that the difference between V_p with and without vibration exceeds 0.0001 V. A new t test was performed to test the hypothesis that the difference does not exceed 0.0002 V. Sample data for these sensors at their respective conditions does not suggest a difference in excess of 0.0002 V using the t and F tests. These sensors prove to be the most sensitive and therefore dictate the vibration sensitivity limit of the module at the specific axis orientation and vibration frequency. Using the most sensitive sensor of the module at each axis orientation and vibration frequency, sensitivity specifications are found. Vibration sensitivity specifications for M4 are given in Table 21 in terms of percent of full-scale output per g (%F.S.O./g).

CONCLUSIONS

The pressure sensors of wide-temperature module M4 are sensitive to vibration. With an application of 20, 55, and 75 Hz along each axis of the module, measured pressure voltages deviate less than 0.0002 V from the non-vibration condition. The module is most sensitive to vibration along the X-axis at a vibration frequency of 20 Hz. Along the Y and Z-axes, vibration sensitivity is greatest at a frequency of 55 Hz. Sensitivity is minimal at a vibration frequency of 75 Hz along the X, Y, and Z-axes. The vibration sensitivity specification ranges from 0.0067% F.S.O./g (75 Hz, all orientations) to 0.0190% F.S.O./g (20 Hz, X-axis orientation).

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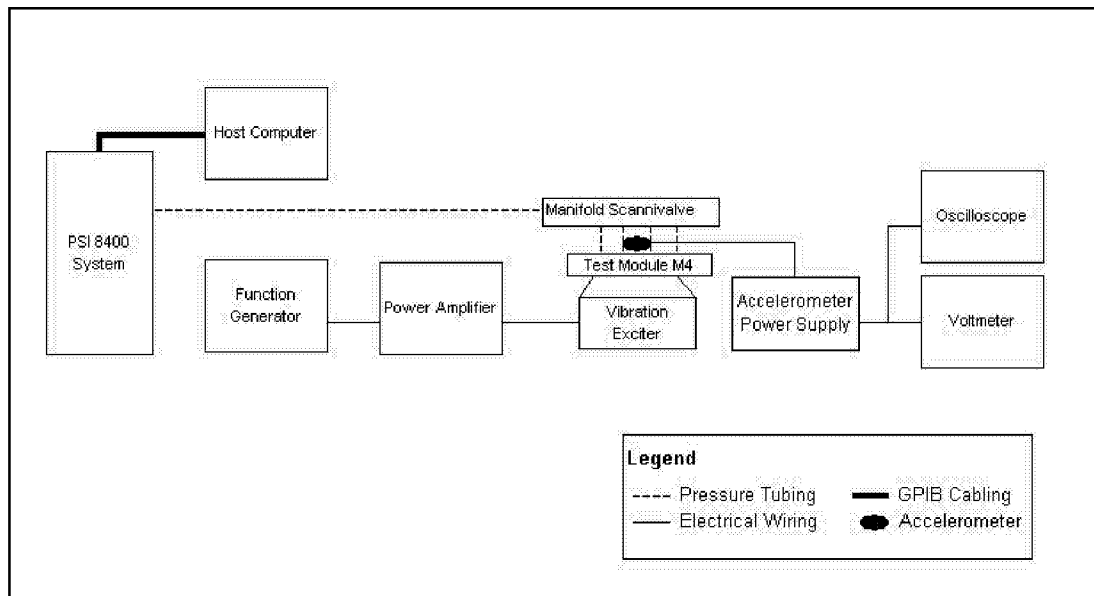


Figure 1. Block diagram of instrumentation used during vibration testing of module M4.

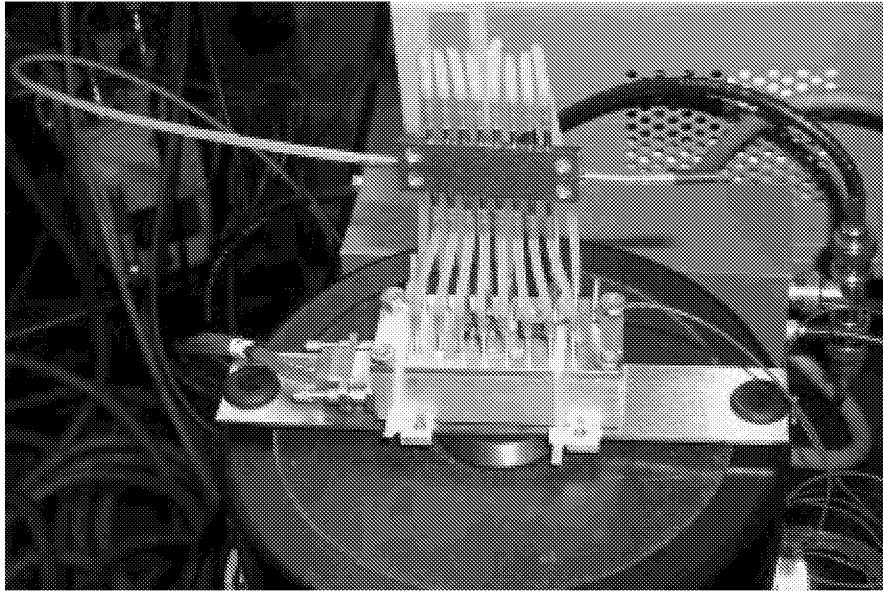


Figure 2. Test module M4 and vibration exciter.

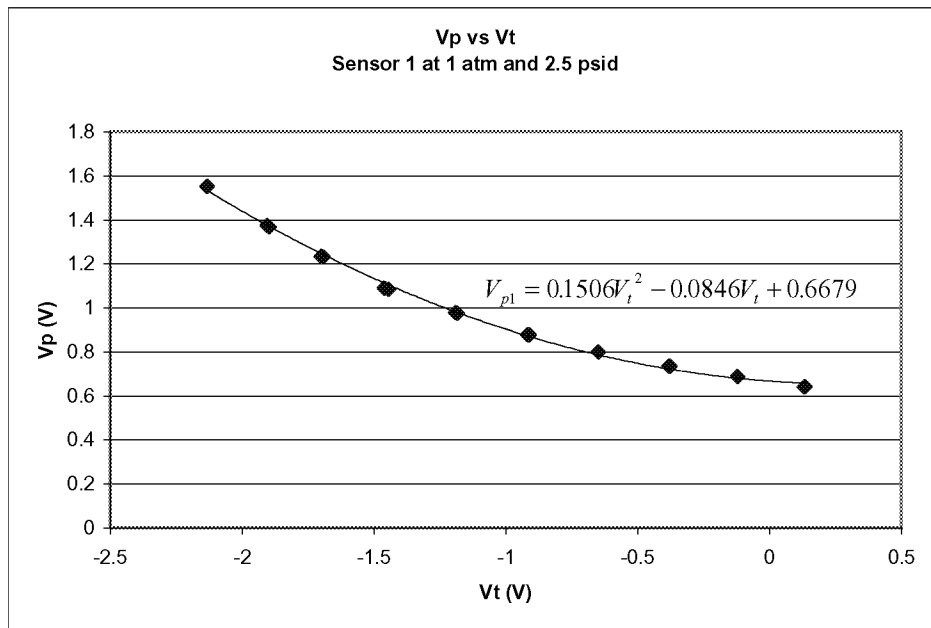


Figure 3. Variation of V_p versus V_t with least squares fit through sample data.

Table 1. Test V_p data with corresponding slopes and corrected values of V_p for sensor 1 at a vibration frequency of 20 Hz along the module's Z-axis.

$P = 2.5$ psid			$P = -2.5$ psid		
V_p (V)	S^+	$V_{p\text{ cor}}$ (V)	V_p (V)	S^-	$V_{p\text{ cor}}$ (V)
0.6947	-0.1063	0.6947	-1.0458	0.0821	-1.0457
0.6949	-0.1062	0.6949	-1.0457	0.0821	-1.0456
0.6947	-0.1057	0.6949	-1.0458	0.0819	-1.0458
0.6946	-0.1062	0.6946	-1.0457	0.0820	-1.0456
0.6944	-0.1053	0.6947	-1.0460	0.0819	-1.0460
0.6946	-0.1055	0.6948	-1.0460	0.0820	-1.0459
0.6947	-0.1058	0.6948	-1.0458	0.0819	-1.0458
0.6949	-0.1050	0.6953	-1.0458	0.0820	-1.0457
0.6949	-0.1060	0.6950	-1.0457	0.0818	-1.0457
0.6947	-0.1056	0.6949	-1.0458	0.0821	-1.0457

Table 2. $V_{p\text{ cor}}$ data with and without vibration for sensor 1 at a vibration frequency of 55 Hz along the module's Z-axis at 2.5 psid ($V_{t0} = -0.0691$ V).

$P = 2.5$ psid							
Without Vibration				With Vibration			
V_p (V) ^a	S^+	$V_t - V_{t0}$ (V) ^a	$V_{p\text{ cor}}$ (V) ^b	V_p (V) ^a	S^+	$V_t - V_{t0}$ (V) ^a	$V_{p\text{ cor}}$ (V) ^b
0.6947	-	-	0.6947	0.6944	-0.105338	0.0003	0.6944
0.6947	-0.1055	-0.0002	0.6947	0.6944	-0.105157	0.0009	0.6945
0.6946	-0.1054	1E-04	0.6946	0.6946	-0.105881	-0.0015	0.6944
0.6947	-0.1054	1E-04	0.6947	0.6947	-0.105399	1E-04	0.6947
0.6947	-0.1053	0.0003	0.6947	0.6944	-0.105579	-0.0005	0.6943
0.6949	-0.1053	0.0003	0.6949	0.6946	-0.104645	0.0026	0.6949
0.6947	-0.1048	0.0021	0.6949	0.6944	-0.1057	-0.0009	0.6943
0.6947	-0.1053	0.0003	0.6947	0.6946	-0.104284	0.0038	0.6950
0.6947	-0.1055	-0.0003	0.6947	0.6947	-0.105067	0.0012	0.6948
0.6947	-0.1057	-0.0009	0.6946	0.6946	-0.105157	0.0009	0.6947
Number of elements n_1			10	Number of elements n_2			10
Mean \bar{x}_1			0.694729	Mean \bar{x}_2			0.694612
Standard deviation s_1			0.00013	Standard deviation s_2			0.00024

^a Measured data

^b See equation (1)

Table 3. F and t test results for module M4 at 20 Hz vibration along the module's Z-axis with 2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	1.105392	$\sigma_1^2 = \sigma_2^2$	0.140567	2.332315	$ D \leq 0.0001V$
2	0.427136	$\sigma_1^2 = \sigma_2^2$	-0.84333	3.855081	$ D \leq 0.0001V$
3	2.453984	$\sigma_1^2 = \sigma_2^2$	-0.13115	2.844534	$ D \leq 0.0001V$
4	1.235373	$\sigma_1^2 = \sigma_2^2$	-0.0535	3.398453	$ D \leq 0.0001V$
5	1.279234	$\sigma_1^2 = \sigma_2^2$	-0.66965	3.220233	$ D \leq 0.0001V$
7	1.091504	$\sigma_1^2 = \sigma_2^2$	-2.72024	0.531516	$ D \leq 0.0001V$
8	1.319459	$\sigma_1^2 = \sigma_2^2$	-1.64851	0.549516	$ D \leq 0.0001V$
9	0.630203	$\sigma_1^2 = \sigma_2^2$	-1.59834	1.773553	$ D \leq 0.0001V$
10	0.27655	$\sigma_1^2 = \sigma_2^2$	-1.29458	2.56604	$ D \leq 0.0001V$
12	1.883749	$\sigma_1^2 = \sigma_2^2$	-2.1955	1.436059	$ D \leq 0.0001V$
13	0.538728	$\sigma_1^2 = \sigma_2^2$	-1.74992	2.288494	$ D \leq 0.0001V$
15	1.23923	$\sigma_1^2 = \sigma_2^2$	-3.00388	1.398929	$ D \leq 0.0001V$
16	0.59005	$\sigma_1^2 = \sigma_2^2$	-1.91574	2.510711	$ D \leq 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001 V$;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001 V$;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 4. F and t test results for module M4 at 20 Hz vibration along the module's Z-axis with -2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	0.327871	$\sigma_1^2 = \sigma_2^2$	-1.47942	2.799945	$ D \leq 0.0001V$
2	2.485344	$\sigma_1^2 = \sigma_2^2$	-3.31666	2.46035	$ D \leq 0.0001V$
3	1.148925	$\sigma_1^2 = \sigma_2^2$	-2.24445	2.539494	$ D \leq 0.0001V$
4	2.936468	$\sigma_1^2 = \sigma_2^2$	-4.08636	0.542475	$ D \leq 0.0001V$
5	2.179707	$\sigma_1^2 = \sigma_2^2$	-3.06978	0.666927	$ D \leq 0.0001V$
7	2.809535	$\sigma_1^2 = \sigma_2^2$	-3.77329	1.217868	$ D \leq 0.0001V$
8	1.464354	$\sigma_1^2 = \sigma_2^2$	-4.12266	1.531007	$ D \leq 0.0001V$
9	2.171634	$\sigma_1^2 = \sigma_2^2$	-2.82696	1.878426	$ D \leq 0.0001V$
10	3.337513	$\sigma_1^2 = \sigma_2^2$	-2.84418	2.429719	$ D \leq 0.0001V$
12	1.541011	$\sigma_1^2 = \sigma_2^2$	-3.06916	1.184374	$ D \leq 0.0001V$
13	0.644933	$\sigma_1^2 = \sigma_2^2$	-4.75646	3.576064	$ D \leq 0.0001V$
15	1.649663	$\sigma_1^2 = \sigma_2^2$	-2.9049	0.470214	$ D \leq 0.0001V$
16	0.958261	$\sigma_1^2 = \sigma_2^2$	-3.74864	0.536434	$ D \leq 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001 V$;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001 V$;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 5. F and t test results for module M4 at 55 Hz vibration along the module's Z-axis with 2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	0.220974	$\sigma_1^2 \neq \sigma_2^2$	0.201616	2.588288	$ D \leq 0.0001V$
2	0.114444	$\sigma_1^2 \neq \sigma_2^2$	0.749299	4.653274	$ D \leq 0.0001V$
3	0.682992	$\sigma_1^2 = \sigma_2^2$	1.588915	4.781291	$ D \leq 0.0001V$
4	0.339694	$\sigma_1^2 = \sigma_2^2$	1.170785	5.222843	$ D \leq 0.0001V$
5	0.111454	$\sigma_1^2 \neq \sigma_2^2$	0.734505	4.490543	$ D \leq 0.0001V$
7	0.201228	$\sigma_1^2 \neq \sigma_2^2$	2.060115	5.532652	$ D > 0.0001V$
8	0.688923	$\sigma_1^2 = \sigma_2^2$	-0.28412	3.133915	$ D \leq 0.0001V$
9	0.685352	$\sigma_1^2 = \sigma_2^2$	1.820167	6.681654	$ D > 0.0001V$
10	0.346783	$\sigma_1^2 = \sigma_2^2$	0.308952	3.210758	$ D \leq 0.0001V$
12	0.963785	$\sigma_1^2 = \sigma_2^2$	1.46757	5.151728	$ D \leq 0.0001V$
13	8.640912	$\sigma_1^2 \neq \sigma_2^2$	-0.39632	5.553148	$ D \leq 0.0001V$
15	4.501851	$\sigma_1^2 \neq \sigma_2^2$	0.69172	5.014225	$ D \leq 0.0001V$
16	0.565998	$\sigma_1^2 = \sigma_2^2$	1.161383	5.532144	$ D \leq 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001 V$;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001 V$;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 6. F and t test results for module M4 at 55 Hz vibration along the module's Z-axis with -2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	1.480202	$\sigma_1^2 = \sigma_2^2$	0.450699	5.503179	$ D \leq 0.0001V$
2	2.601641	$\sigma_1^2 = \sigma_2^2$	-1.32644	2.264722	$ D \leq 0.0001V$
3	1.571199	$\sigma_1^2 = \sigma_2^2$	-0.35372	3.76275	$ D \leq 0.0001V$
4	1.512009	$\sigma_1^2 = \sigma_2^2$	-1.50607	3.768269	$ D \leq 0.0001V$
5	2.032951	$\sigma_1^2 = \sigma_2^2$	-1.00146	3.047385	$ D \leq 0.0001V$
7	3.993334	$\sigma_1^2 = \sigma_2^2$	-0.27538	4.184707	$ D \leq 0.0001V$
8	1.190111	$\sigma_1^2 = \sigma_2^2$	-1.42577	3.147091	$ D \leq 0.0001V$
9	2.075054	$\sigma_1^2 = \sigma_2^2$	-1.01328	2.26536	$ D \leq 0.0001V$
10	12.45744	$\sigma_1^2 \neq \sigma_2^2$	0.28512	4.053945	$ D \leq 0.0001V$
12	1.226427	$\sigma_1^2 = \sigma_2^2$	0.065586	3.376099	$ D \leq 0.0001V$
13	2.14898	$\sigma_1^2 = \sigma_2^2$	-1.61298	4.09279	$ D \leq 0.0001V$
15	1.9846	$\sigma_1^2 = \sigma_2^2$	-0.10716	3.844389	$ D \leq 0.0001V$
16	0.415774	$\sigma_1^2 = \sigma_2^2$	-0.86251	3.057958	$ D \leq 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001 V$;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001 V$;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 7. F and t test results for module M4 at 75 Hz vibration along the module's Z-axis with 2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	0.832078	$\sigma_1^2 = \sigma_2^2$	-0.56814	3.051614	$ D \leq 0.0001V$
2	2.006425	$\sigma_1^2 = \sigma_2^2$	-0.73252	4.981974	$ D \leq 0.0001V$
3	1.20914	$\sigma_1^2 = \sigma_2^2$	0.113649	4.2864	$ D \leq 0.0001V$
4	2.682833	$\sigma_1^2 = \sigma_2^2$	-0.26375	3.430675	$ D \leq 0.0001V$
5	0.249969	$\sigma_1^2 = \sigma_2^2$	-0.0629	4.647677	$ D \leq 0.0001V$
7	1.801979	$\sigma_1^2 = \sigma_2^2$	-0.07955	3.65983	$ D \leq 0.0001V$
8	2.886131	$\sigma_1^2 = \sigma_2^2$	-0.4624	5.02267	$ D \leq 0.0001V$
9	1.512762	$\sigma_1^2 = \sigma_2^2$	0.079296	3.257672	$ D \leq 0.0001V$
10	1.138693	$\sigma_1^2 = \sigma_2^2$	-0.53193	6.380804	$ D \leq 0.0001V$
12	5.321346	$\sigma_1^2 \neq \sigma_2^2$	-0.88507	3.719883	$ D \leq 0.0001V$
13	4.909822	$\sigma_1^2 \neq \sigma_2^2$	-0.90372	3.788061	$ D \leq 0.0001V$
15	0.767192	$\sigma_1^2 = \sigma_2^2$	0.351638	4.53148	$ D \leq 0.0001V$
16	0.518076	$\sigma_1^2 = \sigma_2^2$	-1.52721	3.805092	$ D \leq 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001 V$;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001 V$;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 8. F and t test results for module M4 at 75 Hz vibration along the module's Z-axis with -2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	1.019798	$\sigma_1^2 = \sigma_2^2$	-0.82925	3.215963	$ D \leq 0.0001V$
2	0.74237	$\sigma_1^2 = \sigma_2^2$	-0.07533	3.836582	$ D \leq 0.0001V$
3	1.800536	$\sigma_1^2 = \sigma_2^2$	-1.95481	2.393926	$ D \leq 0.0001V$
4	0.516531	$\sigma_1^2 = \sigma_2^2$	-0.96555	2.479212	$ D \leq 0.0001V$
5	1.08276	$\sigma_1^2 = \sigma_2^2$	-1.8346	1.80843	$ D \leq 0.0001V$
7	0.891242	$\sigma_1^2 = \sigma_2^2$	-0.74363	3.527416	$ D \leq 0.0001V$
8	1.054519	$\sigma_1^2 = \sigma_2^2$	-1.15542	2.776087	$ D \leq 0.0001V$
9	0.896545	$\sigma_1^2 = \sigma_2^2$	0.026726	3.313669	$ D \leq 0.0001V$
10	0.730353	$\sigma_1^2 = \sigma_2^2$	0.168232	3.666641	$ D \leq 0.0001V$
12	0.71419	$\sigma_1^2 = \sigma_2^2$	-0.9025	2.714448	$ D \leq 0.0001V$
13	0.90903	$\sigma_1^2 = \sigma_2^2$	-1.84625	2.597914	$ D \leq 0.0001V$
15	1.379132	$\sigma_1^2 = \sigma_2^2$	-1.92129	2.165271	$ D \leq 0.0001V$
16	2.143187	$\sigma_1^2 = \sigma_2^2$	-2.53585	4.578657	$ D \leq 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001 V$;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001 V$;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 9. F and t test results for module M4 at 20 Hz vibration along the module's X-axis with 2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	0.108971	$\sigma_1^2 \neq \sigma_2^2$	-3.530254784	-0.68504	$ D \leq 0.0001V$
2	1.14264	$\sigma_1^2 = \sigma_2^2$	-2.347169827	1.554847	$ D \leq 0.0001V$
3	0.939272	$\sigma_1^2 = \sigma_2^2$	-3.64805011	0.214049	$ D \leq 0.0001V$
4	0.101315	$\sigma_1^2 \neq \sigma_2^2$	-4.236239738	0.631312	$ D \leq 0.0001V$
5	0.562643	$\sigma_1^2 = \sigma_2^2$	-2.599498602	0.696248	$ D \leq 0.0001V$
7	1.15337	$\sigma_1^2 = \sigma_2^2$	-2.658211614	0.34986	$ D \leq 0.0001V$
8	1.650757	$\sigma_1^2 = \sigma_2^2$	-1.551345214	1.052091	$ D \leq 0.0001V$
9	0.816952	$\sigma_1^2 = \sigma_2^2$	-2.596475841	2.001756	$ D \leq 0.0001V$
10	0.261634	$\sigma_1^2 = \sigma_2^2$	-3.603026729	1.34852	$ D \leq 0.0001V$
12	0.500307	$\sigma_1^2 = \sigma_2^2$	-4.217602194	-0.39755	$ D \leq 0.0001V$
13	0.631609	$\sigma_1^2 = \sigma_2^2$	-2.653192638	1.078873	$ D \leq 0.0001V$
15	0.605372	$\sigma_1^2 = \sigma_2^2$	-2.801363572	0.987106	$ D \leq 0.0001V$
16	1.009481	$\sigma_1^2 = \sigma_2^2$	-2.00289342	1.255823	$ D \leq 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001 V$;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001 V$;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 10. F and t test results for module M4 at 20 Hz vibration along the module's X-axis with -2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	3.321735	$\sigma_1^2 = \sigma_2^2$	2.053388	6.105714	$ D > 0.0001V$
2	2.700724	$\sigma_1^2 = \sigma_2^2$	0.381078	4.167873	$ D \leq 0.0001V$
3	1.557725	$\sigma_1^2 = \sigma_2^2$	1.760765	4.368039	$ D > 0.0001V$
4	0.781087	$\sigma_1^2 = \sigma_2^2$	1.37505	5.403459	$ D \leq 0.0001V$
5	0.552065	$\sigma_1^2 = \sigma_2^2$	1.27984	4.688528	$ D \leq 0.0001V$
7	2.156863	$\sigma_1^2 = \sigma_2^2$	1.694469	5.683143	$ D \leq 0.0001V$
8	0.687425	$\sigma_1^2 = \sigma_2^2$	0.76379	4.268698	$ D \leq 0.0001V$
9	4.547906	$\sigma_1^2 \neq \sigma_2^2$	-0.26877	4.142169	$ D \leq 0.0001V$
10	0.533919	$\sigma_1^2 = \sigma_2^2$	1.379126	4.135916	$ D \leq 0.0001V$
12	0.428907	$\sigma_1^2 = \sigma_2^2$	3.80053	8.881959	$ D > 0.0001V$
13	1.025765	$\sigma_1^2 = \sigma_2^2$	1.026116	4.548931	$ D \leq 0.0001V$
15	1.320168	$\sigma_1^2 = \sigma_2^2$	1.477432	4.282129	$ D \leq 0.0001V$
16	1.16582	$\sigma_1^2 = \sigma_2^2$	2.388049	6.299406	$ D > 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001 V$;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001 V$;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 11. F and t test results for module M4 at 55 Hz vibration along the module's X-axis with 2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	1.029203	$\sigma_1^2 = \sigma_2^2$	-4.516817018	-1.38691	$ D \leq 0.0001V$
2	0.082409	$\sigma_1^2 \neq \sigma_2^2$	-3.154761988	1.617642	$ D \leq 0.0001V$
3	0.85161	$\sigma_1^2 = \sigma_2^2$	-2.070039068	1.393593	$ D \leq 0.0001V$
4	1.287521	$\sigma_1^2 = \sigma_2^2$	-3.727048586	-0.3518	$ D \leq 0.0001V$
5	0.300277	$\sigma_1^2 = \sigma_2^2$	-2.00163114	2.188466	$ D \leq 0.0001V$
7	0.146846	$\sigma_1^2 \neq \sigma_2^2$	-1.896675449	1.732017	$ D \leq 0.0001V$
8	1.797447	$\sigma_1^2 = \sigma_2^2$	-1.865580295	0.606513	$ D \leq 0.0001V$
9	0.37995	$\sigma_1^2 = \sigma_2^2$	-4.444286012	-0.31178	$ D \leq 0.0001V$
10	1.661673	$\sigma_1^2 = \sigma_2^2$	-4.23818339	-0.23065	$ D \leq 0.0001V$
12	0.391684	$\sigma_1^2 = \sigma_2^2$	-4.597923116	1.066115	$ D \leq 0.0001V$
13	0.470019	$\sigma_1^2 = \sigma_2^2$	-3.921510825	-0.83823	$ D \leq 0.0001V$
15	0.979465	$\sigma_1^2 = \sigma_2^2$	-3.253186128	0.031188	$ D \leq 0.0001V$
16	0.370694	$\sigma_1^2 = \sigma_2^2$	-3.421389175	0.26618	$ D \leq 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001 V$;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001 V$;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 12. F and t test results for module M4 at 55 Hz vibration along the module's X-axis with -2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	2.257986	$\sigma_1^2 = \sigma_2^2$	0.317175	5.446961	$ D \leq 0.0001V$
2	7.756158	$\sigma_1^2 \neq \sigma_2^2$	0.442141	4.98433	$ D \leq 0.0001V$
3	3.718876	$\sigma_1^2 = \sigma_2^2$	0.199331	4.994062	$ D \leq 0.0001V$
4	2.125813	$\sigma_1^2 = \sigma_2^2$	0.237656	3.377833	$ D \leq 0.0001V$
5	0.719575	$\sigma_1^2 = \sigma_2^2$	1.675893	6.161361	$ D \leq 0.0001V$
7	0.29442	$\sigma_1^2 = \sigma_2^2$	0.849721	6.052868	$ D \leq 0.0001V$
8	2.793378	$\sigma_1^2 = \sigma_2^2$	0.125089	3.647716	$ D \leq 0.0001V$
9	1.721894	$\sigma_1^2 = \sigma_2^2$	0.058869	3.205598	$ D \leq 0.0001V$
10	3.497715	$\sigma_1^2 = \sigma_2^2$	0.983341	6.859024	$ D \leq 0.0001V$
12	0.32042	$\sigma_1^2 = \sigma_2^2$	0.272093	5.699543	$ D \leq 0.0001V$
13	2.597925	$\sigma_1^2 = \sigma_2^2$	-0.58087	5.368566	$ D \leq 0.0001V$
15	4.435529	$\sigma_1^2 \neq \sigma_2^2$	-0.38421	3.574573	$ D \leq 0.0001V$
16	0.993187	$\sigma_1^2 = \sigma_2^2$	-0.88894	4.514749	$ D \leq 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001 V$;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001 V$;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 13. F and t test results for module M4 at 75 Hz vibration along the module's X-axis with 2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	0.45834	$\sigma_1^2 = \sigma_2^2$	-2.554164927	-0.02655	$ D \leq 0.0001V$
2	1.926768	$\sigma_1^2 = \sigma_2^2$	-2.172041784	3.521112	$ D \leq 0.0001V$
3	2.964696	$\sigma_1^2 = \sigma_2^2$	-2.18996986	0.80873	$ D \leq 0.0001V$
4	1.29676	$\sigma_1^2 = \sigma_2^2$	-2.363112058	1.672711	$ D \leq 0.0001V$
5	6.485486	$\sigma_1^2 \neq \sigma_2^2$	-1.823824226	3.845375	$ D \leq 0.0001V$
7	1.921418	$\sigma_1^2 = \sigma_2^2$	-0.559967131	3.231272	$ D \leq 0.0001V$
8	1.905788	$\sigma_1^2 = \sigma_2^2$	-2.429621363	0.200257	$ D \leq 0.0001V$
9	0.847151	$\sigma_1^2 = \sigma_2^2$	-0.237771352	4.473691	$ D \leq 0.0001V$
10	1.518538	$\sigma_1^2 = \sigma_2^2$	-3.196324804	0.273356	$ D \leq 0.0001V$
12	1.005207	$\sigma_1^2 = \sigma_2^2$	-2.988061914	1.273971	$ D \leq 0.0001V$
13	0.493702	$\sigma_1^2 = \sigma_2^2$	-1.60838819	2.549792	$ D \leq 0.0001V$
15	0.361736	$\sigma_1^2 = \sigma_2^2$	-2.713525767	2.977941	$ D \leq 0.0001V$
16	1.467924	$\sigma_1^2 = \sigma_2^2$	-1.394294518	3.659217	$ D \leq 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001 V$;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001 V$;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 14. F and t test results for module M4 at 75 Hz vibration along the module's X-axis with -2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	0.319557	$\sigma_1^2 = \sigma_2^2$	-0.80865	2.263535	$ D \leq 0.0001V$
2	0.63112	$\sigma_1^2 = \sigma_2^2$	-1.72515	3.267172	$ D \leq 0.0001V$
3	0.611338	$\sigma_1^2 = \sigma_2^2$	-1.04072	2.953575	$ D \leq 0.0001V$
4	0.414453	$\sigma_1^2 = \sigma_2^2$	-1.80394	2.434189	$ D \leq 0.0001V$
5	1.155283	$\sigma_1^2 = \sigma_2^2$	-1.77543	2.591225	$ D \leq 0.0001V$
7	0.199509	$\sigma_1^2 \neq \sigma_2^2$	-2.22563	2.584757	$ D \leq 0.0001V$
8	0.54722	$\sigma_1^2 = \sigma_2^2$	0.007172	3.527585	$ D \leq 0.0001V$
9	1.273978	$\sigma_1^2 = \sigma_2^2$	-1.40832	1.603162	$ D \leq 0.0001V$
10	0.180293	$\sigma_1^2 \neq \sigma_2^2$	-0.65974	2.155914	$ D \leq 0.0001V$
12	0.741803	$\sigma_1^2 = \sigma_2^2$	-2.02475	1.901253	$ D \leq 0.0001V$
13	0.367781	$\sigma_1^2 = \sigma_2^2$	-0.96684	4.203167	$ D \leq 0.0001V$
15	0.835331	$\sigma_1^2 = \sigma_2^2$	-0.09865	3.530594	$ D \leq 0.0001V$
16	0.921414	$\sigma_1^2 = \sigma_2^2$	-1.56012	1.706072	$ D \leq 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001$ V;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001$ V;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 15 F and t test results for module M4 at 20z vibration along the module's Y-axis with 2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	0.507925	$\sigma_1^2 = \sigma_2^2$	-5.10927	-1.341211769	$ D \leq 0.0001V$
2	0.266782	$\sigma_1^2 = \sigma_2^2$	-4.9304	0.424899782	$ D \leq 0.0001V$
3	0.97168	$\sigma_1^2 = \sigma_2^2$	-2.32867	0.510064361	$ D \leq 0.0001V$
4	1.82963	$\sigma_1^2 = \sigma_2^2$	-1.75269	1.132976618	$ D \leq 0.0001V$
5	0.768817	$\sigma_1^2 = \sigma_2^2$	-3.65122	0.188443261	$ D \leq 0.0001V$
7	1.729644	$\sigma_1^2 = \sigma_2^2$	-4.61533	-0.705389426	$ D \leq 0.0001V$
8	0.960321	$\sigma_1^2 = \sigma_2^2$	-1.14135	1.175140379	$ D \leq 0.0001V$
9	1.894075	$\sigma_1^2 = \sigma_2^2$	-2.25788	0.774769288	$ D \leq 0.0001V$
10	1.091163	$\sigma_1^2 = \sigma_2^2$	-4.82169	0.298300395	$ D \leq 0.0001V$
12	0.379674	$\sigma_1^2 = \sigma_2^2$	-2.7647	0.484845441	$ D \leq 0.0001V$
13	1.324691	$\sigma_1^2 = \sigma_2^2$	-1.98262	1.496687217	$ D \leq 0.0001V$
15	1.264985	$\sigma_1^2 = \sigma_2^2$	-6.64443	-1.597552065	$ D \leq 0.0001V$
16	0.661774	$\sigma_1^2 = \sigma_2^2$	-4.36577	0.191109213	$ D \leq 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001 V$;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001 V$;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 16. F and t test results for module M4 at 20z vibration along the module's Y-axis with -2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	0.589092	$\sigma_1^2 = \sigma_2^2$	-0.80767	1.914375	$ D \leq 0.0001V$
2	0.589092	$\sigma_1^2 = \sigma_2^2$	-1.22985	2.219874	$ D \leq 0.0001V$
3	0.589092	$\sigma_1^2 = \sigma_2^2$	-2.22808	1.638883	$ D \leq 0.0001V$
4	0.589092	$\sigma_1^2 = \sigma_2^2$	-2.66941	1.172381	$ D \leq 0.0001V$
5	0.589092	$\sigma_1^2 = \sigma_2^2$	-1.57576	1.78098	$ D \leq 0.0001V$
7	0.589092	$\sigma_1^2 = \sigma_2^2$	-1.58502	1.771545	$ D \leq 0.0001V$
8	0.589092	$\sigma_1^2 = \sigma_2^2$	-2.0995	1.598031	$ D \leq 0.0001V$
9	0.589092	$\sigma_1^2 = \sigma_2^2$	-2.22922	0.652257	$ D \leq 0.0001V$
10	0.589092	$\sigma_1^2 = \sigma_2^2$	-0.64506	2.600604	$ D \leq 0.0001V$
12	0.589092	$\sigma_1^2 = \sigma_2^2$	-1.66994	3.373834	$ D \leq 0.0001V$
13	0.589092	$\sigma_1^2 = \sigma_2^2$	-2.29269	1.635148	$ D \leq 0.0001V$
15	0.589092	$\sigma_1^2 = \sigma_2^2$	0.243474	3.103975	$ D \leq 0.0001V$
16	0.589092	$\sigma_1^2 = \sigma_2^2$	-2.55855	4.63061	$ D \leq 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001 V$;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001 V$;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 17. F and t test results for module M4 at 55z vibration along the module's Y-axis with 2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	0.613784	$\sigma_1^2 = \sigma_2^2$	-6.308799799	-1.71263	$ D \leq 0.0001V$
2	0.460813	$\sigma_1^2 = \sigma_2^2$	-4.323440649	0.418494	$ D \leq 0.0001V$
3	0.403791	$\sigma_1^2 = \sigma_2^2$	-3.887820467	-0.05124	$ D \leq 0.0001V$
4	0.757802	$\sigma_1^2 = \sigma_2^2$	-4.154668399	-0.25403	$ D \leq 0.0001V$
5	1.155783	$\sigma_1^2 = \sigma_2^2$	-3.56491324	0.066755	$ D \leq 0.0001V$
7	0.946845	$\sigma_1^2 = \sigma_2^2$	-4.332838244	-0.92539	$ D \leq 0.0001V$
8	0.471391	$\sigma_1^2 = \sigma_2^2$	-8.110427549	-2.89991	$ D > 0.0001V$
9	0.387073	$\sigma_1^2 = \sigma_2^2$	-6.349951356	-0.61359	$ D \leq 0.0001V$
10	0.50443	$\sigma_1^2 = \sigma_2^2$	-5.344342143	-0.25156	$ D \leq 0.0001V$
12	1.381358	$\sigma_1^2 = \sigma_2^2$	-4.709559099	-0.92498	$ D \leq 0.0001V$
13	0.753343	$\sigma_1^2 = \sigma_2^2$	-8.734039639	-0.38669	$ D \leq 0.0001V$
15	1.091931	$\sigma_1^2 = \sigma_2^2$	-4.520005389	-0.68294	$ D \leq 0.0001V$
16	0.623748	$\sigma_1^2 = \sigma_2^2$	-6.107161213	0.562584	$ D \leq 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001 V$;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001 V$;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 18. F and t test results for module M4 at 55z vibration along the module's Y-axis with -2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	1.421036	$\sigma_1^2 = \sigma_2^2$	-1.36576	1.996729	$ D \leq 0.0001V$
2	1.257621	$\sigma_1^2 = \sigma_2^2$	-1.58995	2.484282	$ D \leq 0.0001V$
3	0.600572	$\sigma_1^2 = \sigma_2^2$	-1.90679	2.32946	$ D \leq 0.0001V$
4	1.394943	$\sigma_1^2 = \sigma_2^2$	-0.73637	3.308183	$ D \leq 0.0001V$
5	0.878861	$\sigma_1^2 = \sigma_2^2$	-1.82222	2.393193	$ D \leq 0.0001V$
7	0.900858	$\sigma_1^2 = \sigma_2^2$	-3.23138	4.753267	$ D \leq 0.0001V$
8	1.237972	$\sigma_1^2 = \sigma_2^2$	-2.36859	2.731737	$ D \leq 0.0001V$
9	0.272556	$\sigma_1^2 = \sigma_2^2$	-1.76822	1.849279	$ D \leq 0.0001V$
10	0.885877	$\sigma_1^2 = \sigma_2^2$	-1.3559	3.621855	$ D \leq 0.0001V$
12	0.185648	$\sigma_1^2 \neq \sigma_2^2$	-0.17161	4.375902	$ D \leq 0.0001V$
13	0.838303	$\sigma_1^2 = \sigma_2^2$	-0.10077	4.564482	$ D \leq 0.0001V$
15	0.57171	$\sigma_1^2 = \sigma_2^2$	-0.06672	2.937095	$ D \leq 0.0001V$
16	0.226903	$\sigma_1^2 \neq \sigma_2^2$	-2.4412	2.068876	$ D \leq 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001 V$;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001 V$;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 19. F and t test results for module M4 at 75z vibration along the module's Y-axis with 2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	1.080795	$\sigma_1^2 = \sigma_2^2$	1.078004002	5.681561	$ D \leq 0.0001V$
2	0.345619	$\sigma_1^2 = \sigma_2^2$	-0.241634092	3.963406	$ D \leq 0.0001V$
3	3.812474	$\sigma_1^2 = \sigma_2^2$	0.216751314	4.314074	$ D \leq 0.0001V$
4	1.013617	$\sigma_1^2 = \sigma_2^2$	0.930668979	4.244615	$ D \leq 0.0001V$
5	0.729342	$\sigma_1^2 = \sigma_2^2$	-0.538972168	3.299588	$ D \leq 0.0001V$
7	0.848376	$\sigma_1^2 = \sigma_2^2$	0.842854762	4.006135	$ D \leq 0.0001V$
8	0.784933	$\sigma_1^2 = \sigma_2^2$	1.187256112	4.86488	$ D \leq 0.0001V$
9	1.739687	$\sigma_1^2 = \sigma_2^2$	-0.783363878	3.54215	$ D \leq 0.0001V$
10	1.730347	$\sigma_1^2 = \sigma_2^2$	0.300422259	3.748454	$ D \leq 0.0001V$
12	0.738371	$\sigma_1^2 = \sigma_2^2$	-2.702233527	3.786136	$ D \leq 0.0001V$
13	3.449477	$\sigma_1^2 = \sigma_2^2$	-0.814400343	3.699711	$ D \leq 0.0001V$
15	0.541197	$\sigma_1^2 = \sigma_2^2$	0.762016756	4.342881	$ D \leq 0.0001V$
16	0.622028	$\sigma_1^2 = \sigma_2^2$	-0.328321387	3.489273	$ D \leq 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001 V$;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001 V$;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 20. F and t test results for module M4 at 75z vibration along the module's Y-axis with -2.5 psid.

Sensor	F statistic ^a	Conclusion	t statistic ^b	t statistic ^c	Conclusion
1	0.440907	$\sigma_1^2 = \sigma_2^2$	-2.60436	0.50388	$ D \leq 0.0001V$
2	0.335249	$\sigma_1^2 = \sigma_2^2$	-3.08448	1.579682	$ D \leq 0.0001V$
3	0.834889	$\sigma_1^2 = \sigma_2^2$	-2.60822	1.667686	$ D \leq 0.0001V$
4	0.774919	$\sigma_1^2 = \sigma_2^2$	-3.09824	2.149411	$ D \leq 0.0001V$
5	0.746934	$\sigma_1^2 = \sigma_2^2$	-3.26374	0.882395	$ D \leq 0.0001V$
7	2.110689	$\sigma_1^2 = \sigma_2^2$	-2.57564	0.235406	$ D \leq 0.0001V$
8	0.947163	$\sigma_1^2 = \sigma_2^2$	-2.80616	0.250869	$ D \leq 0.0001V$
9	0.70971	$\sigma_1^2 = \sigma_2^2$	-1.87047	1.003665	$ D \leq 0.0001V$
10	0.400272	$\sigma_1^2 = \sigma_2^2$	-3.27243	0.417397	$ D \leq 0.0001V$
12	0.714049	$\sigma_1^2 = \sigma_2^2$	-2.92545	0.594814	$ D \leq 0.0001V$
13	0.727685	$\sigma_1^2 = \sigma_2^2$	-3.7431	0.777037	$ D \leq 0.0001V$
15	0.936723	$\sigma_1^2 = \sigma_2^2$	-3.34144	0.563746	$ D \leq 0.0001V$
16	0.327097	$\sigma_1^2 = \sigma_2^2$	-2.51423	0.311141	$ D \leq 0.0001V$

^a $0.248 \leq F \leq 4.03 = H_0$ accepted ($\sigma_1^2 = \sigma_2^2$)

$0.248 > F > 4.03 = H_0$ rejected ($\sigma_1^2 \neq \sigma_2^2$)

^b For $D = 0.0001 V$;

$t < 1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t < 1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

^c For $D = -0.0001 V$;

$t > -1.73$ for acceptance if $\sigma_1^2 = \sigma_2^2$

$t > -1.83$ for acceptance if $\sigma_1^2 \neq \sigma_2^2$

Table 21. Vibration specifications of module M4 in terms of percent of full-scale output per g (%F.S.O./g).

<u>Vibration Frequency</u> <u>(Hz)</u>	<u>X-axis Orientation</u>	<u>Y-axis Orientation</u>	<u>Z-axis Orientation</u>
20	0.0190	0.0095	0.0095
55	0.0067	0.0133	0.0133
75	0.0067	0.0067	0.0067

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13. ABSTRACT (Maximum 200 words) A vibration sensitivity test was conducted on a Wide-Temperature ESP module. The test object was Module "M4," a 16-channel, 4 psi unit scheduled for installation in the Arc Sector of NTF. The module was installed on a vibration exciter and loaded to positive then negative full-scale pressures (± 2.5 psid). Test variables were the following: Vibration frequencies: 20, 55, 75 Hz. Vibration level: 1 g. Vibration axes: X, Y, Z. The pressure response was measured on each channel, first without and then with the vibration turned on, and the difference analyzed by means of the statistical t-test. The results show that the vibration sensitivity does not exceed 0.01% Full Scale Output per g (with the exception of one channel on one axis) to a 95 percent confidence level. This specification, limited by the resolution of the pressure source, lies well below the total uncertainty specification of 0.1 percent Full Scale Output.				
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